International Congress on Economics, Management and Business Studies
Hosted Online from New York, USA
Date: 23rd May , 2026
Website: https://econferencia.com

COMPARATIVE ANALYSIS OF TECHNOLOGIES FOR HYDROGEN PRODUCTION FROM PLASTIC WASTE

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Abstract

This article presents a comparative scientific analysis of the main technologies used for hydrogen production from plastic waste, with emphasis on thermochemical, catalytic, microwave-assisted, plasma-assisted, hydrothermal, and emerging electrochemical or photo-reforming routes. The relevance of the topic is determined by two parallel global challenges: the rapid accumulation of plastic waste and the need to expand low-carbon hydrogen production. According to the OECD, global plastics production increased from 234 million tonnes in 2000 to 460 million tonnes in 2019, while plastic waste rose from 156 million tonnes to 353 million tonnes over the same period; only about 9% of plastic waste was ultimately recycled, whereas 19% was incinerated and almost half was landfilled. At the same time, conventional hydrogen production remains strongly fossil-dependent: the International Energy Agency reported that global hydrogen production emitted 920 Mt CO_2 in 2023, with nearly two-thirds produced from unabated natural gas and about one-fifth from unabated coal. In this context, plastic-to-hydrogen conversion can be considered not as a universal solution to plastic pollution, but as a technically significant waste-to-value pathway for non-recyclable, mixed, contaminated, or multilayer plastic streams. The article compares conventional pyrolysis, pyrolysis–catalytic steam reforming, gasification, microwave-assisted pyrolysis, plasma-assisted conversion, supercritical water treatment, catalytic dry reforming, oxidative steam reforming, and emerging routes such as photo-reforming and electro-reforming. The

comparison shows that pyrolysis alone is technically simple but produces hydrogen-rich gases only as one fraction of a wider oil–gas–char product spectrum, while integrated pyrolysis–steam reforming–water gas shift systems provide higher hydrogen selectivity and better compatibility with pressure swing adsorption or membrane separation. Gasification is more suitable for continuous large-scale operation and mixed feedstocks but requires strict control of temperature, steam/carbon ratio, equivalence ratio, tar formation, chlorine release, and downstream gas cleaning. Microwave-assisted pyrolysis offers selective heating, lower tar formation potential, and energy-saving prospects, but scale-up is limited by microwave penetration depth, feedstock dielectric variability, and equipment cost. Plasma and supercritical water processes can process difficult waste streams but face high energy intensity, reactor material challenges, and economic uncertainty. The study concludes that the most industrially realistic pathway in the near term is not a single technology, but a hybrid system combining feedstock pretreatment, dechlorination, staged pyrolysis or gasification, catalytic reforming, water–gas shift, hydrogen purification, and carbon management.

Keywords: plastic waste, hydrogen production, pyrolysis, gasification, steam reforming, catalytic reforming, microwave-assisted pyrolysis, plasma gasification, syngas, circular economy, low-carbon hydrogen, waste-to-energy.

Introduction

Plastic waste has become one of the most difficult anthropogenic waste streams to manage because it is chemically durable, compositionally heterogeneous, logistically dispersed, and frequently contaminated by food residues, additives, pigments, fillers, halogens, metals, and multilayer packaging components.

Mechanical recycling remains the preferred option for clean, sorted, single-polymer plastics, but it cannot absorb the entire waste stream because mixed polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride, composite films, thermosets, and contaminated packaging often lose quality during repeated processing or cannot be economically separated. Therefore, technologies that convert non-recyclable plastic waste into fuels, chemicals, syngas, or hydrogen have attracted increasing attention. Hydrogen production from plastic waste is technically attractive because most commodity plastics, especially polyethylene and polypropylene, contain high mass fractions of carbon and hydrogen, and their depolymerization can generate hydrocarbons, methane, light gases, and reformable vapours. However, the idea must be evaluated critically. Plastic-derived hydrogen is not automatically “green” or “zero-carbon”; its environmental performance depends on the waste source, sorting method, process energy, catalyst durability, CO_2 capture, chlorine and sulphur management, char handling, hydrogen purification, and avoided disposal route. If plastic waste is converted to hydrogen without carbon capture, with high external fossil energy input, and with poor control of toxic by-products, the technology may simply shift pollution from solid waste to air emissions. If, however, the process treats non-recyclable plastic that would otherwise be landfilled, openly burned, exported, or incinerated, and if the conversion system integrates catalytic reforming, water–gas shift, gas cleaning, hydrogen separation, and carbon capture or carbon product utilization, it can become a serious component of circular waste management and low-carbon fuel production. Recent reviews describe plastic gasification as a route involving depolymerization, reforming, tar and char formation, and gasification reactions, with hydrogen yield affected by plastic type, operating temperature, steam/carbon ratio, equivalence ratio, and catalysts. Similarly, pyrolysis-derived syngas

reviews emphasize that hydrogen production depends on feedstock composition, heating rate, residence time, pressure, catalysts, and downstream separation, while palladium-based membranes and pressure swing adsorption can improve hydrogen purity. The scientific problem, therefore, is not whether hydrogen can be obtained from plastic waste — it can — but which technology provides the best compromise between hydrogen yield, process stability, feedstock flexibility, energy demand, scale-up feasibility, environmental safety, and economic viability. This article aims to compare the major plastic-to-hydrogen technologies using IMRAD logic and to identify the conditions under which each route is technically reasonable or weak. The central thesis is direct: conventional pyrolysis is useful as a first conversion stage but insufficient as a dedicated hydrogen technology; gasification is robust but difficult to clean and decarbonize without advanced gas treatment; catalytic pyrolysis–reforming systems offer high hydrogen potential but are vulnerable to catalyst deactivation; microwave and plasma systems are promising but not yet universally mature; hydrothermal and emerging reforming routes are scientifically interesting but require careful techno-economic validation before industrial adoption.

Materials and Methods

The methodological basis of this article is a comparative analytical review of plastic-to-hydrogen technologies according to technological mechanism, feedstock compatibility, process temperature, reactor complexity, product distribution, hydrogen selectivity, catalyst requirement, energy intensity, environmental risk, and industrial scalability. The technologies considered include conventional thermal pyrolysis, catalytic pyrolysis, pyrolysis–catalytic steam reforming, pyrolysis–dry reforming, oxidative steam reforming, gasification with air, oxygen or steam, plasma-assisted gasification, microwave-

assisted pyrolysis, supercritical water conversion, photo-reforming, electro-reforming, and integrated multi-stage systems with water–gas shift and hydrogen purification. The feedstocks considered are the most common plastic waste fractions: high-density polyethylene, low-density polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride, mixed municipal plastic waste, multilayer packaging, and contaminated industrial plastics. In comparative terms, polyethylene and polypropylene are favourable for hydrogen-rich gas production because they are hydrocarbon polymers with high H/C ratios and relatively low oxygen content, whereas PET introduces oxygenated species, char formation tendencies, and different gas compositions, and PVC introduces chlorine, HCl release, corrosion, catalyst poisoning, and dioxin-related risk if poorly controlled. The assessment criteria were divided into six groups. The first group is chemical efficiency: hydrogen yield, syngas composition, methane reformability, tar content, carbon conversion, and water–gas shift compatibility. The second group is energy efficiency: operating temperature, external heat demand, heat recovery potential, microwave or plasma electricity demand, steam requirement, and hydrogen purification energy. The third group is operational reliability: feeding behaviour, melting and stickiness, char formation, fouling, slagging, catalyst coking, chlorine poisoning, and reactor continuity. The fourth group is environmental safety: CO_2 generation, acid gas formation, halogen release, heavy metal transfer, toxic organic by-products, and carbon capture possibility. The fifth group is economic feasibility: reactor complexity, catalyst cost, equipment lifetime, gas cleaning burden, scale-up maturity, and product market integration. The sixth group is circular-economy relevance: whether the route competes with mechanical recycling, whether it treats genuinely non-recyclable plastics, whether it recovers valuable hydrogen rather than merely destroying waste, and whether residual carbon can be captured or converted into useful products. For analytical comparison, the overall hydrogen production pathway was represented as a sequence of operations: plastic waste collection and sorting → pretreatment and removal of PVC/metals/moisture → thermal or catalytic decomposition → reforming or gasification → water–gas shift reaction → gas cleaning → hydrogen separation by PSA, membrane, or absorption → CO_2 management → residue treatment. In pyrolysis–steam reforming systems, the core reactions include polymer cracking to hydrocarbons, steam reforming of hydrocarbons into CO and H_2, and water–gas shift conversion of CO and H_2O into CO_2 and additional H_2. In gasification, partial oxidation and steam gasification reactions provide heat and syngas formation, but the gas composition depends strongly on temperature, oxidant type, equivalence ratio, steam input, residence time, and catalyst presence. In microwave-assisted pyrolysis, energy is delivered electromagnetically and converted into heat through dielectric losses, often requiring microwave absorbers or catalysts because many plastics have low microwave absorption; recent work notes advantages in heat distribution, lower energy consumption potential, reduced tar formation, and improved hydrogen selectivity, but also emphasizes scale-up problems related to variable dielectric properties, limited penetration depth, hot spots, feeding instability, and expensive microwave equipment. This methodology deliberately avoids ranking technologies by hydrogen yield alone, because high hydrogen yield in a laboratory reactor may be misleading if the system requires pure feedstock, noble catalysts, high steam consumption, high electricity input, or unrealistic separation conditions. Instead, the comparison treats hydrogen yield as one necessary criterion among several, with industrial feasibility and environmental integrity given equal weight.

Results

The comparative analysis shows that the technologies can be grouped into three practical maturity levels: near-term industrially plausible systems, medium-term intensified systems, and early-stage emerging systems. The first group includes gasification, pyrolysis followed by catalytic steam reforming, and multi-stage pyrolysis–reforming–water gas shift systems. These routes are closest to industrial relevance because they resemble existing thermochemical and syngas-processing infrastructure. Conventional pyrolysis decomposes plastics in the absence of oxygen at elevated temperatures and produces liquid oil, gas, wax, and char. Its strength is simplicity, tolerance of polyolefin-rich feedstocks, and ability to convert plastic into reformable vapours. Its weakness is that hydrogen is not the main product unless pyrolysis is coupled with downstream reforming; otherwise, the gas fraction may contain methane, ethylene, propylene, light hydrocarbons, CO, CO_2, and limited hydrogen depending on temperature and catalyst use. Therefore, pyrolysis alone is better understood as a plastic depolymerization and hydrocarbon-generation step rather than a full hydrogen-production technology. Pyrolysis–catalytic steam reforming is stronger because volatile hydrocarbons from the first stage are passed through a reforming catalyst, usually nickel-based or noble-metal-based, in the presence of steam. This increases hydrogen selectivity and allows later water–gas shift conversion. A 2025 study on optimized mixed plastic pyrolysis–reforming reported a multi-stage framework integrating slow pyrolysis, in-line steam reforming, water–gas shift reactors, and pressure swing adsorption; it found that increasing reforming temperature from 500 °C to 1000 °C increased hydrogen yield by 83.53%, although gains beyond 700 °C became limited, and a steam-to-plastic ratio of two improved production efficiency. This result is technically important because it shows both the promise and the tradeoff: higher temperature improves conversion

but eventually gives diminishing returns, and excessive steam can improve reforming but increase heat demand and downstream condensation load. Three-stage pyrolysis–steam reforming–water gas shift systems are particularly logical because they mimic conventional hydrogen production: plastic vapours replace natural gas as the reforming feed, and CO produced during reforming is further converted to H_2 via water–gas shift. Experimental work on household, commercial, and industrial plastic wastes has emphasized that pyrolysis followed by in-line catalytic steam reforming is a promising development route for hydrogen-rich syngas, with tar minimization as a major advantage when the reforming stage is properly designed. Gasification is the second major near-term pathway. Unlike pyrolysis, it uses limited oxygen, air, steam, or oxygen–steam mixtures to convert plastic into syngas. Its strengths are continuous operation potential, high carbon conversion, compatibility with existing gasification knowledge, and possibility of integration with CCUS. Its weaknesses are tar formation, feeding problems caused by molten plastic stickiness, acid gas formation from PVC, ash and additive management, and high requirements for gas cleaning before hydrogen separation or downstream fuel-cell use. Plastic gasification is particularly sensitive to temperature, steam/carbon ratio, equivalence ratio, plastic type, and catalyst, and the literature highlights that co-feeding biomass or coal waste may reduce tar and improve feeding behaviour, although this changes the carbon accounting and must be assessed carefully. The second maturity group includes microwave-assisted pyrolysis, plasma-assisted gasification, catalytic dry reforming, and oxidative steam reforming. Microwave-assisted pyrolysis can heat selectively and rapidly, potentially reducing thermal gradients and tar formation, but industrial scale-up is not trivial. The problem is brutal but simple: plastic waste is heterogeneous, many polymers are poor microwave absorbers, and a laboratory microwave reactor does not automatically

translate into a continuous industrial system with stable feeding, uniform field distribution, and controlled product quality. Plasma-assisted processes can reach very high temperatures, crack tars effectively, and treat difficult feedstocks, but their electricity demand and electrode/reactor durability can undermine economic feasibility unless low-cost renewable power and high-value hydrogen or syngas use are available. Dry reforming uses CO_2 as a reforming agent and can convert hydrocarbons into H_2 and CO, which is attractive for carbon utilization narratives, but it often suffers from catalyst coking and requires high temperature; it may be better as a syngas-adjustment step than as a standalone universal solution. Oxidative steam reforming combines partial oxidation and steam reforming, balancing endothermic and exothermic heat effects; it can reduce external heat demand, but oxygen control is critical because excessive oxidation sacrifices hydrogen yield and converts valuable carbon into CO_2. The third group includes supercritical water conversion, photo-reforming, electro-reforming, and flash Joule heating-related routes. Supercritical water systems can process wet or contaminated waste without full drying and may promote reforming chemistry in a dense water medium, but reactor corrosion, salt deposition, pressure requirements, and capital cost are major barriers. Photo-reforming and electro-reforming are scientifically attractive because they promise lower-temperature hydrogen production under light or electrochemical driving forces, but current practical use is limited by catalyst stability, low reaction rates for real plastics, surface-area constraints, pretreatment requirements, and difficulty processing solid heterogeneous waste at scale. Overall, the results indicate that the highest near-term potential belongs to integrated thermochemical systems rather than single-step processes. The best-performing conceptual route is: sorted non-recyclable polyolefin-rich plastic → dechlorination/PVC removal → staged pyrolysis → catalytic steam reforming → water–gas shift → CO_2 capture → PSA or membrane hydrogen purification. For mixed and dirty plastic streams, oxygen–steam gasification with robust tar cracking and acid gas cleaning may be more realistic. For decentralized or modular applications, microwave-assisted catalytic pyrolysis could become competitive if equipment cost and scale-up problems are solved. For very contaminated or hazardous plastic waste, plasma may be technically capable but economically severe. Thus, the comparison does not support a simplistic ranking such as “pyrolysis is best” or “gasification is best”; it supports technology matching by waste type, scale, energy source, carbon-management strategy, and final hydrogen purity requirement.

Discussion

The strongest conclusion from the comparison is that plastic-to-hydrogen technology must be judged by system boundaries, not by reactor performance alone. A paper may report high hydrogen yield from clean polyethylene pellets under controlled laboratory conditions, but real municipal plastic waste contains moisture, dirt, labels, multilayer films, PET, PVC, additives, colourants, metals, and biological residues. These impurities change feeding behaviour, catalyst life, acid gas load, char formation, and gas cleaning cost. Therefore, any claim that plastic waste can be converted into “clean hydrogen” is incomplete unless it states the feedstock composition, pretreatment requirement, energy source, catalyst life, CO_2 management, and residue disposal route. The first major tradeoff is between feedstock flexibility and product quality. Gasification is more flexible for mixed waste, but produces a complex raw gas requiring tar reforming, particulate removal, acid gas scrubbing, water–gas shift adjustment, and hydrogen separation. Pyrolysis–steam reforming can generate cleaner hydrogen-rich gas if the feedstock is controlled, but it is more vulnerable to catalyst deactivation by chlorine, sulphur, metals, and coke. Microwave-assisted pyrolysis can reduce some heat-transfer limitations, yet it introduces electromagnetic design challenges that are not present in conventional reactors. Plasma can destroy tars and difficult molecules, but it risks becoming an expensive waste destruction process rather than an efficient hydrogen production technology. The second major tradeoff is between hydrogen yield and energy demand. High temperature generally improves cracking and reforming, but beyond a certain point the incremental hydrogen gain may not justify extra heat input, catalyst sintering risk, or reactor material stress. The same logic applies to steam-to-plastic ratio: steam is necessary for reforming and water–gas shift, but excessive steam consumes heat, increases condenser load, dilutes product gas, and reduces overall energy efficiency. The third tradeoff concerns carbon. Plastics are carbon-rich materials, and converting them to hydrogen inevitably leaves carbon somewhere: in CO_2, CO, char, carbon black, wax, oil, or solid residues. If the carbon leaves as uncaptured CO_2, the hydrogen may be lower-waste but not necessarily low-carbon. If carbon is captured or converted into durable carbon materials, the environmental profile improves. This is why gasification reviews increasingly discuss CCUS integration, and why pyrolysis systems that generate solid carbon or valuable carbon materials may deserve attention where stable markets exist. The fourth tradeoff concerns circularity. Plastic-to-hydrogen should not be used as an excuse to burn or chemically process plastics that could be mechanically recycled with lower environmental burden. Its rational application is for residual, contaminated, multilayer, or degraded plastics that cannot be mechanically recycled into useful products. In policy terms, this technology belongs below reduction, reuse, and high-quality mechanical recycling, but above landfill, uncontrolled burning, and possibly conventional incineration when hydrogen recovery and carbon management are effective. The fifth tradeoff concerns chlorine. PVC may be a small fraction of mixed plastic waste by mass, but it can dominate operational risk because HCl corrodes equipment, poisons catalysts, damages membranes, and creates downstream environmental hazards. Any industrial plastic-to-hydrogen plant must include PVC identification, sorting, dechlorination, sorbents, or acid gas scrubbing. Ignoring chlorine is not a minor omission; it is a scale-up failure mode. The sixth tradeoff concerns hydrogen purification. Producing hydrogen-containing syngas is not the same as producing market-grade hydrogen. Fuel cells and many chemical uses require high-purity hydrogen, and impurities such as CO, H_2S, HCl, NH_3, tars, and particulates must be removed. Pressure swing adsorption is mature, while palladium-based membranes can achieve very high purity but face cost, poisoning, and durability limitations; recent syngas-focused reviews discuss membrane separation, including palladium and palladium–silver membranes, as promising but technically sensitive purification routes. From an industrial engineering perspective, the most credible development pathway is modular integration rather than technology isolation. A serious plant should include: feedstock acceptance standards; sorting and shredding; PVC and metal control; drying only when necessary; a controlled thermal conversion unit; catalytic reforming or gasification; tar cracking; heat recovery; water–gas shift; gas cleaning; CO_2 capture or utilization; hydrogen separation; and safe handling of char, ash, brine, or spent catalyst. Such a plant is more complex than a simple pyrolysis reactor, but simplicity at the wrong boundary creates false economics. A cheap reactor with expensive gas cleaning, rapid catalyst deactivation, poor hydrogen purity, and uncontrolled emissions is not a viable hydrogen technology. Conversely, an integrated system with higher capital cost may be more viable if it achieves stable operation, high hydrogen recovery, low emissions, and useful co-products. The practical recommendation is therefore staged adoption: first, treat relatively clean industrial polyolefin waste using pyrolysis–steam reforming; second, test mixed municipal plastics using oxygen–steam gasification with strong gas cleaning; third, develop microwave-assisted catalytic modules for specific controlled waste streams; fourth, reserve plasma and supercritical systems for difficult wastes where disposal cost, environmental hazard, or policy incentives justify higher energy demand. The final hard question is economic: can plastic-derived hydrogen compete with natural gas reforming, electrolysis, or biomass gasification? Without carbon pricing, waste treatment credits, avoided landfill/incineration costs, or high-purity hydrogen premiums, the answer may often be no. With waste management fees, renewable heat or electricity, carbon capture, and local hydrogen demand, the answer can become yes for selected regions and feedstocks. Thus, plastic-to-hydrogen is not a magic solution; it is a conditional technology whose success depends on honest feedstock classification, disciplined process integration, and rigorous carbon accounting.

Conclusion

The comparative analysis demonstrates that hydrogen production from plastic waste is scientifically feasible and industrially promising, but only under clearly defined technical, environmental, and economic conditions. Conventional pyrolysis is useful as a first-stage depolymerization process, but it should not be treated as a dedicated hydrogen production technology unless it is integrated with catalytic reforming and water–gas shift conversion. Pyrolysis–catalytic steam reforming offers one of the strongest near-term routes because it can convert plastic vapours into hydrogen-rich gas and can be coupled with PSA or membrane purification, but its weaknesses are catalyst coking, chlorine poisoning, steam demand, and feedstock sensitivity. Gasification is more robust for mixed plastic waste and continuous large-scale operation, yet it requires high-temperature control, tar reforming, acid gas treatment, syngas conditioning, and carbon management. Microwave-assisted pyrolysis is promising for energy-efficient and selective heating, but its industrial maturity is limited by feedstock dielectric variability, microwave penetration depth, continuous feeding problems, and equipment cost. Plasma-assisted systems and supercritical water conversion can process difficult wastes, but high energy intensity, reactor durability, pressure, corrosion, and capital cost restrict broad application. Emerging photo-reforming and electro-reforming routes are scientifically valuable but currently more appropriate for research and niche applications than for large-scale mixed plastic waste treatment. The most realistic strategy is therefore not to search for a single "best" technology, but to match technology to waste stream: clean polyolefin-rich industrial waste is suitable for pyrolysis–steam reforming; mixed municipal plastic waste may be better suited to oxygen–steam gasification; wet or contaminated streams may require hydrothermal or plasma-assisted options only when justified by waste hazard and treatment cost; and microwave-assisted systems may become competitive for modular controlled-feedstock applications. For an OAK-level scientific conclusion, the core statement is this: plastic-to-hydrogen technologies should be evaluated by integrated system performance — hydrogen yield, energy input, catalyst lifetime, gas cleaning, carbon capture, residue safety, and circular-economy hierarchy — rather than by laboratory hydrogen yield alone. The smallest technically sound improvement for future research is to stop studying ideal single-polymer pellets only and to move toward real mixed plastic waste, controlled PVC content, long-duration catalyst testing, full material-energy balance, life-cycle assessment, and techno-economic analysis. Only then can plastic waste hydrogen production move from a promising laboratory concept to a credible industrial technology.

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